Unraveling the nature of coherent pulsar radio emission

Dipanjan Mitra

National Centre for Radio Astrophysics Ganeshkhind, Pune 411 007 India

Janusz Gil and George I. Melikidze[1]

J.Kepler Institute of Astronomy, University of Zielona Gora, Poland

dmitra@ncra.tifr.res.in,jag@astro.ia.uz.zgora.pl,gogi@astro.ia.uz.zgora.pl

ABSTRACT

Forty years have passed since the discovery of pulsars, yet the physical mechanism of their coherent radio emission is a mystery. Recent observational and theoretical studies strongly suggest that the radiation outcoming from the pulsar magnetosphere consists mainly of extraordinary waves polarized perpendicular to the planes of pulsar dipolar magnetic field. However, the fundamental question whether these waves are excited by maser or coherent curvature radiation, remains open. High quality single pulse polarimetry is required to distinguish between these two possible mechanisms. Here we showcase such *decisive* strong single pulses from 10 pulsars observed with the GMRT, showing extremely high linear polarization with the position angle following locally the mean position angle traverse. These pulses, which are relatively free from depolarization, must consist of exclusively single polarization mode. We associate this mode with the extraordinary wave excited by the coherent curvature radiation. This crucial observational signature enables us to argue, for the first time, in favor of the coherent curvature emission mechanism, excluding the maser mechanism.

Subject headings: pulsars: general — radiation mechanisms: nonthermal

1. Introduction

Pulsar coherent radio emission originates within the flux tube of the open force lines of dipolar magnetic field. This conclusion is unavoidable from the theoretical point of view as

[1]Georgian National Astrophysical Observatory, Chavchavadze State University, Kazbegi 2a, Tbilisi, Georgia

these are the only field lines that can develop an ultra-high potential drop acting as a basic source of pulsar activity (Goldreich & Julian 1969). As the pulsar emission beam sweeps past the observer a single radio pulse is observed, which typically consists of one to several subpulses. Each subpulse is emitted within a sub-bundle of the overall flux tube of the open field lines. When a large number of single pulses are added together in phase, then a stable mean or average profile is obtained. These profiles consist of one to several components, with an actual number depending on how close the observer's line-of-sight (LOS) approaches the pulsar beam axis. In the case of small approach angle (called the impact angle), the mean profile consists of a central (core) component, usually flanked by one or two pairs of conal components (Backer 1976, Rankin 1993). The position angle (PA) of the linear polarization across the average pulse profile shows a characteristic S-swing or traverse, which is associated with a range of open magnetic field line planes intersected by LOS (Radhakrishnan & Cooke 1969). This swing is usually steep under the core component, but is much shallower or even flat under the outer conal components. The model describing this swing is commonly known as the rotating vector model (RVM). Canonically, the RVM holds for average profiles, without specifying what kind of PA variation should be expected for a single pulse (subpulse) emission. We address this problem below in this paper.

Early polarimetric studies revealed that single pulses in pulsar radiation are highly linearly polarized, with moderate, sign-changing circular polarization observed in some cases (see for e.g. Clark & Smith 1969, Lyne, Smith & Graham 1971, Manchester, Taylor & Huguenin 1975). However, none of these observations were transparent enough to pin down the emission mechanism. Here we present a set of high quality single pulse polarimetric observations from the Giant Meterwave Radio Telescope (GMRT, Swarup et al. 1991) with an aim to identify the pulsar emission process.

2. Results

A bright subpulse in a single pulse from the radio pulsar PSR B1237+25 observed at 325 MHz is shown in Fig. 1. The subpulse, which appears at the conal region, is close to a gaussian shape, with a full width half maximum of about 0.7°. It is very highly linearly polarized (93% at the peak) and the circular polarization changes sign close to the subpulse maximum. The most notable finding is that the *PA of linear polarization in subpulses follow closely the mean PA curve at the corresponding profile components.* Generally, when a highly polarized single pulses appear the subpulse PA variations follow the mean PA traverse. We use this crucial observational feature in our data to identify the mechanism of pulsar radio emission. Fig. 2 shows similar subpulses from 9 more pulsars, all of them are the conal

components of their respective pulses.

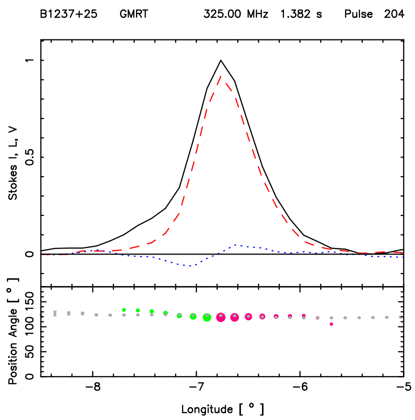

Fig. 1.— The plot shows a strong subpulse in a single pulse of PSR B1237+25. The top panel of the plot shows a symmetric pulse which is highly linearly polarized, has a sign changing circular where the peak of the total intensity (in black), peak of linear (red) polarization and zero of circular (blue) lie close to each other. The bottom panel shows the position angle (PA) traverse for the average PA traverse obtained from a larger set of pulses in light gray and the PA traverse of the subpulse is shown in green and magenta colors corresponding to negative and positive circular polarization respectively. This signature is typical of curvature radiation as discussed in the text.

The observations were done at 325 MHz with the phased array mode of the GMRT. A bandwidth of 16 MHz was used and the data was recorded at a sampling interval of 0.512 ms. About 2% accuracy in the stokes parameters were obtained by applying the polarization calibration procedure (Mitra, Gupta & Kudale 2005). The calibrated stokes were used to construct the linear polarization $\mathrm{L} = \sqrt{\mathrm{U}^2 + \mathrm{Q}^2}$ and the $\mathrm{PA} = 0.5\tan^{-1}(\mathrm{U}/\mathrm{Q})$. The convention followed for the circular polarization V is Left–Hand–Circular - Right–Hand–Circular.

3. Discussion

Before we proceed to understand the implications of the observations in Figs. 1 and 2, we need to discuss how coherent radio emission can originate and escape from the magnetospheric plasma. Generally speaking, the coherent pulsar radio emission should be generated by means of either a maser or coherent curvature mechanism (Ginzburg & Zheleznyakov 1975, Kazbegi, Machabeli & Melikidze 1991). This radiation, while propagating in the magnetosphere splits naturally into the ordinary and extraordinary waves, which correspond to the normal modes of strongly magnetized plasma (see e.g. Arons & Barnard 1986). The

ordinary waves are polarized in the plane of the wave vector k and the local magnetic field direction and their electric field has a component along the magnetic line of force. Therefore they interact strongly with plasma particles and thus encounter difficulty in escaping the magnetosphere. On the other hand, the extraordinary waves are linearly polarized perpendicularly to the wave vector k and the local magnetic field. As a result they can propagate through the magnetospheric plasma almost as in vacuum and thus reach the observer (see Gil, Lyubarsky & Melikidze 2004, (hereafter GLM04) for a detailed discussion on the nature of ordinary and extraordinary waves in pulsar magnetosphere).

Interestingly, the X-ray image of the Vela pulsar can give an insight to the pulsar's emission geometry. The absolute orientation of the polarization plane found in this case definitely demonstrates that the polarization direction of radio waves from the Vela pulsar is perpendicular to the planes of dipolar magnetic field lines (Lai, Chernoff & Cordes 1991). Therefore, undoubtedly this radiation consists of extraordinary waves (see also discussion in Section 6.4 in GLM04). Also, based on the assumption that pulsar's proper motions are parallel to the rotation axis (Johnston et al. 2005, Rankin 2007), it was argued that the primary polarization mode for pulsar PSR B0329+54 corresponds to the extraordinary mode (Mitra, Rankin & Gupta 2007). These conclusions strengthen the argument that the observed pulsar radiation consists mainly of extraordinary waves polarized perpendicular to the planes of dipolar magnetic field lines. It is worth emphasizing that for the first time the radiation of point like charge moving along the curved magnetic field lines in the relativistic electron-positron plasma of the pulsar magnetosphere was self-consistently treated by GLM04. They found the exact solution of the corresponding set of Maxwell equations in the far zone to be the extraordinary wave mode. Thus, they demonstrated, that the extraordinary mode can be generated in strong curved magnetic field via the linear coupling of the normal modes in the radiation formation region (see also Section 5 in GLM04).

However, an open question remains i.e. what kind of input coherent radiation excites these waves emanating from the pulsar? This question can be answered based on the highly polarized subpulse for 10 pulsars presented in this paper. Theoretically, excitation of escaping waves in pulsar magnetosphere is possible either by maser or coherent curvature emission mechanisms. The subpulse width in the case of maser mechanism corresponds to the opening angle of the maser emission which depends on the resonant conditions necessary for the plasma instability to be developed (Kazbegi, Machabeli, Melikidze & Smirnova 1991). In maser radiation the k vector can be oriented in any direction with respect to the local magnetic field. As we already mentioned, the electric vector of the extraordinary waves is perpendicular to the plane containing both k and magnetic field vector B_0, while the position angle of the ordinary waves lies in this plane. Thus, in case of maser radiation, the PA (orientation of electric field vector E) across the subpulse width should perform swings,

rather than remain tightly aligned with the mean PA traverse which reflects the orientation of the magnetic field plane, as per RVM. This is illustrated for the extraordinary mode in the upper panel of Fig. 3, where the electric field E changes direction for different viewing angles defined by k vectors. In contrast, the curvature radiation is highly collimated along the local magnetic field B_0. Additionally, the electric vector excited by the coherent curvature emission in plasma must be either perpendicular or parallel to the plane of curvature of the magnetic field lines. Thus, the subpulse PA variation will reflect the change in the orientation of the magnetic field planes, that is the subpulse PA will closely follow the RVM-like mean PA traverse. This is illustrated in the lower panel of Fig. 3 for extraordinary waves, where the electric vectors E are perpendicular to the planes of magnetic field lines. Our observations clearly demonstrate that the observed PA variation across the subpulse follow the mean PA (RVM-like) traverse, implying that the observed emission is due to waves excited by the coherent curvature radiation. As already mentioned, from a theoretical perspective, only the extraordinary wave can escape the pulsar magnetosphere freely, and hence we conjecture that these strong highly polarized single pulses are likely to be freely escaping extraordinary waves excited by coherent curvature radiation.

High linear polarization and sense-reversing circular polarization is a property of curvature radiation from a single charged particle moving relativistically along curved magnetic field lines (Michel 1987). This idea had led to the development of the theory of curvature radiation (Gil & Snakowski 1990 a,b) of small hypothetical charged bunch emitting coherently (Ruderman & Sutherland 1975). In fact, for a gaussian intensity envelope this model can faithfully reproduce the observations reported in Fig. 1 and 2 (Gil, Kijak & Zycki 1993). This theory, however, had serious problems. First, it was developed for vacuum, without considering generation and propagation of the emitted radiation in pulsar magnetospheric plasma. Second, the mechanism for formation of elementary bunches that could emit coherent curvature radiation was unknown. The general opinion was that formation of such bunches was difficult (see Melrose 1995 for review).

Let us now briefly describe the theoretical model capable of forming elementary bunches emitting the coherent curvature radiation. Close to the neutron star where the observed radio emission is found to originate (which is about 300-500 km, see for e g. Rankin 1993, Blaskiewics, Cordes & Wasserman 1981, Kijak & Gil 1997), the well known two-stream plasma instability naturally generates the Langmuir plasma waves (e.g. Asseo & Melikidze 1998). Consequently, a spark-associated soliton model of the coherent pulsar radio emission has been developed (Melikidze, Gil & Pataraya 2000), in which the non-stationary sparking discharge of the ultra-high potential drop just above the polar cap results in modulational instability of Langmuir waves. This leads to formation of small, relativistic, charged solitons, able to emit coherent curvature radiation. So, a natural mechanism for the formation of

charged bunches was found. The only deficiency of the soliton model was that the influence of the ambient plasma on the formation and propagation of the emitted radiation was not considered. Therefore, it was not known whether this radiation can emerge from the pulsar and reach the observer.

This problem has now been addressed and GLM04 found that the power of coherent curvature radiation of a point-like charge (a model of charged soliton) moving relativistically along curved magnetic field lines through the pulsar magnetospheric electron-positron plasma is largely suppressed compared with the vacuum case (in which the power was too high compared with observations). However this power is still at a considerable level to explain the observed pulsar luminosities. The outgoing waves are polarized perpendicularly to the plane of curvature of magnetic field lines, and they represent the escaping extraordinary waves. The polarization properties of the subpulses from 10 pulsars presented in this paper strongly support this theory. Naturally, the above statement is true provided that propagation effects in magnetospheric plasma cannot change the polarization state. As was shown by Cheng & Ruderman (1979) the subpulse polarization patterns can be, in general, affected by the propagation effects if the so called adiabatic walking condition is satisfied. However, a more rigorous treatment for the radiation mechanism considered here demonstrates that the adiabatic walking condition is not satisfied (see eq. [31] and the corresponding discussion below it in GLM04). Therefore the waves escape from the plasma retaining the initial polarization in the direction perpendicular to the magnetic field line planes, exactly as it is observed in strong and highly linearly polarized subpulses presented in our Fig. 2.

The characteristic Lorentz factors of emitting bunches/solitons should be about $\gamma \simeq 400$, for obtaining the observed frequency and power due to coherent curvature radiation in the magnetospheric plasma (GLM04). The typical subpulse widths in Fig. 1 and 2 is about $1^\circ \simeq 2 \times 10^{-2}$ radians, which is several times larger than the width of the radiation cone of an elementary curvature emitter $1/400 = 0.0025$ radians. Thus the subpulse should be formed by the incoherent sum of radiation emitted by a number of solitons filling the flux tube of dipolar field lines with an angular extent of about 0.02 radians in the emission region (which for a typical pulsar with a period of 1 sec originates at an emission altitude of about 50 stellar radii, see for e.g. Melikidze et al. 2000, Kijak & Gil 1997). This angular width projected onto the polar cap surface gives about 1 percent of the fractional area, which is consistent with the model in which the base of the subpulse flux tube is formed by sparks of electron-positron avalanches (e.g. Ruderman & Sutherland 1975, Gil & Sendyk 2000). This leads to generation of coherent curvature radiation as proposed in the spark associated soliton model by Melikidze, Gil & Pataraya (2000).

In this paper we analyse a selection of high quality, almost completely polarized single

pulses from a number of pulsars. We argue that in those cases we observe almost exclusively one polarization mode, which we associate with the extraordinary waves excited by the coherent curvature radiation (GLM04). It should be mentioned that some earlier observations have already found evidence that single pulse PA variations follow the mean PA traverse (see Ramachandran et al. 2002). However those observations do not reveal any highly polarized pulses as shown in this paper. Single pulse depolarization can result from incoherent addition of emission overlapping from adjacent field lines w.r.t the LOS, presence of orthogonal modes and also propagation effects. Our almost completely polarized pulses, are relatively free of depolarization and hence can be associated with one of the polarization mode. In this sense they seem to be ideal to unravel the nature of the pulsar radio emission process. Naturally, based on our selected data we are not able to examine the phenomenon of orthogonally polarized modes. Hence, the question about the origin of orthogonal modes observed in pulsar radio emission is still open. While the answer is not yet clear, we speculate that the usually weaker secondary orthogonal polarization mode is somehow connected with the other (ordinary) mode excited via the coherent curvature radiation. However, there is a theoretical problem to be solved as how the waves polarized in the plane of the curved magnetic field can escape from the magnetosphere?

Finally, a comment on the apparent circular polarization, reversing sense at or near the subpulse maximum, as evident from Figs. 1 and 2. Indeed, the emitted extraordinary waves are purely linearly polarized and the question is whether this is always true for the observed radiation. In case of pulsars the planes of the source motion along curved field lines rotate with respect to the observer and we claim that the observed radiation attains the net circular polarization for geometrical reasons, as discussed in Gil & Snakowski (1990 a,b). Indeed, sense reversing circular polarization in vacuum results from the fact that each source of coherent curvature radiation is viewed from both sides of the plane of their motion as the observer's LOS cuts through a cones of emission (Gil, Kijak & Zycki 1993).

A proper understanding of the pulsar emission mechanism critically depends on our ability to analyze highly turbulent non-linear behavior of plasma. The single pulse polarization in pulsars in conjunction with the spark associated soliton model seems to explain one of the most intriguing phenomenon in astrophysics. We claim that the observed pulsar signals consists mainly of extraordinary waves (at least in the case of strong linearly polarized subpulses) excited in magnetospheric plasma by coherent curvature radiation. It is likely that this development presented here will find application in several other coherent emission process in astrophysics, like giant pulses, RRATs and extrasolar radio bursts.

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REFERENCES

Arons, J & Barnard, J. J., 1986, ApJ, 302, 120

Asseo, E & Melikidze, G. I., 1998, MNRAS, 301, 59

Backer, D. C., 1976, ApJ, 209, 895

Blaskiewicz, M., Cordes, J. M. & Wasserman, I., 1991, ApJ, 370, 643

Clark, R. R. & Smith, F. G., 1969, nature, 221, 724

Gil, J., Kijak, J. & Zycki, P., 1993, A&A, 272, 207

Gil, J., Lyubarsky, Y. & Melikidze, G. I., 2004,ApJ, 600,872 (GLM04)

Gil, J. & Snakowksi, J.K., 1990a, A&A, 234, 237

Gil, J. & Snakowksi, J.K., 1990b, A&A, 234, 269

Gil, J. & Sendyk, M., 2000, ApJ, 541, 351

Ginzburg, V. L. & Zheleznyakov, V. V., 1975, ARA&A, 13, 511

Johnston, S., Hobbs, G., Vigeland, S., Kramer, M., Weisberg, J. M. & Lyne, A. G., 2005, MNRAS, 364, 1397

Kazbegi, A. Z., Machabeli, G. Z. & Melikidze, G. I., 1991, MNRAS, 253, 377

Kazbegi, A. Z., Machabeli, G. Z., Melikidze, G. I. & Smirnova, T., 1991, Astrofizika, 34, 433

Kijak, J. & Gil, J., 1997, MNRAS, 299, 855

Lai, D., Chernoff, D. F., & Cordes, J. M., , ApJ, 549, 1111

Lyne, A. G., Smith, F. G. & Graham, D. A., 1971,MNRAS, 153, 337

Manchester, R. N, Taylor, J. H. & Huguenin, G. R., 1995 , ApJ, 196, 83

Melikidze, G. I., Gil, J. & Pataraya, A. D., 2000, ApJ, 544, 1081

Melrose, D. B., 1995, JApA., 16, 137

Michel, F. C., 1987,ApJ, 322, 822

Mitra, D, Gupta, Y & Kudale, S., 2005, Polarization Calibration of the Phased Array Mode of the GMRT, URSI GA 2005, Commission J03a

Mitra, D, Rankin, J. M. & Gupta, Y., 2007, MNRAS, 379, 932

Radhakrishnan, V., & Cooke, D. J., 1969, ApJLett, 3, 225

Ramachandran, R., Rankin, J. M., Stappers, B. W., Kouwenhoven, M. L. A. & van Leeuwen, A. G. J., 2003, å, 381, 993

Rankin, J. M., 1993, ApJ, 405, 285

Rankin, J. M., 2007, ApJ, 664, 443

Ruderman, M. & Sutherland, P. G., 1975, 196, 51

Swarup, G., Ananthakrishnan, S., Kapahi, V. K., Rao, A. P., Subrahmanya, C. R. & Kulkarni V. K., 1991, Current Science 60, 95

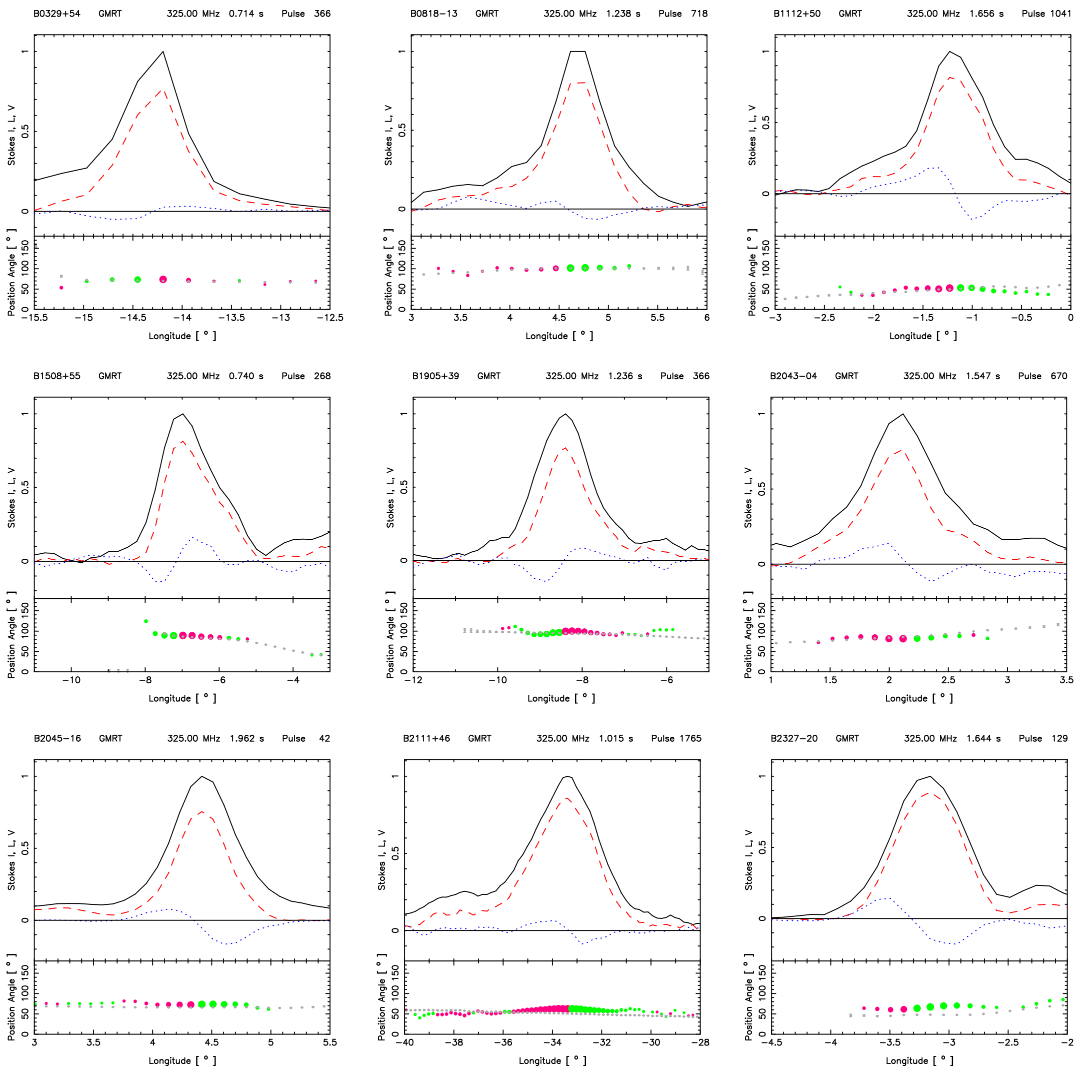

Fig. 2.— Same as in Fig. 1. The subpulses are from pulsars PSRs B0329+54, B0818-13, B1112+50, B1508+55, B1905+39, B2043-04, B2045-16, B2111+46 & B2327-20 (the order is from left to right and top to bottom).

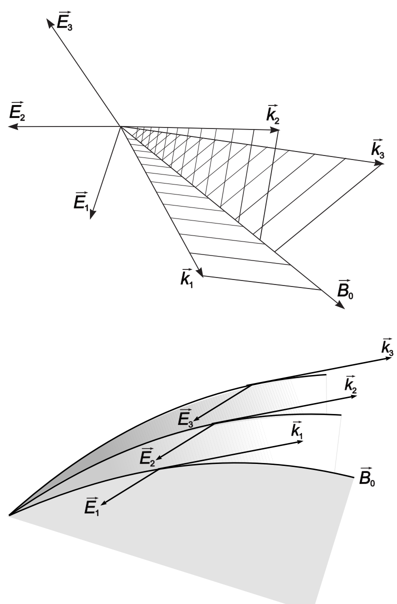

Fig. 3.— Behavior of the wave electric field vector (i.e. the position angle) in the case of maser (upper panel) and curvature (lower panel) emission mechanisms. In the upper panel the position angle alters fast across the subpulse width, while in the lower panel the PA variation are determined by the range of orientations of the planes of dipolar magnetic field lines encompassed by a beam of subpulse emission.